Spatio-temporal dynamics of vegetation in Jungar Banner of China during 2000–2017

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Abstract: It is known that the exploitation of opencast coal mines has seriously damaged the environments in the semi-arid areas. Vegetation status can reliably reflect the ecological degeneration and restoration in the opencast mining areas in the semi-arid areas. Long-time series MODIS NDVI data are widely used to simulate the vegetation cover to reflect the disturbance and restoration of local ecosystems. In this study, both qualitative (linear regression method and coefficient of variation (CoV)) and quantitative (spatial buffer analysis, and change amplitude and the rate of change in the average NDVI) analyses were conducted to analyze the spatio-temporal dynamics of vegetation during 2000–2017 in Jungar Banner of Inner Mongolia Autonomous Region, China, at the large (Jungar Banner and three mine groups) and small (three types of functional areas: opencast coal mining excavation areas, reclamation areas and natural areas) scales. The results show that the rates of change in the average NDVI in the reclamation areas (20%–60%) and opencast coal mining excavation areas (10%–20%) were considerably higher than that in the natural areas (<7%). The vegetation in the reclamation areas experienced a trend of increase (3–5 a after reclamation)-decrease (the sixth year of reclamation)-stability. The vegetation in Jungar Banner has a spatial heterogeneity under the influences of mining and reclamation activities. The ratio of vegetation improvement area to vegetation degradation area in the west, southwest and east mine groups during 2000–2017 was 8:1, 20:1 and 33:1, respectively. The regions with the high CoV of NDVI above 0.45 were mainly distributed around the opencast coal mining excavation areas, and the regions with the CoV of NDVI above 0.25 were mostly located in areas with low (28.8%) and medium-low (10.2%) vegetation cover. The average disturbance distances of mining activities on vegetation in the three mine groups (west, southwest and east) were 800, 800 and 1000 m, respectively. The greater the scale of mining, the farther the disturbance distances of mining activities on vegetation. We conclude that vegetation reclamation will certainly compensate for the negative impacts of opencast coal mining activities on vegetation. Sufficient attention should be paid to the proportional allocation of plant species (herbs and shrubs) in the reclamation areas, and the restored vegetation in these areas needs to be protected for more than 6 a. Then, as the repair time increased, the vegetation condition of the reclamation areas would exceed that of the natural areas.

Keywords: NDVI; spatio-temporal dynamics; linear regression method; mining activities; opencast coal mining areas; reclamation areas; Jungar Banner

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1 Introduction

The environments of opencast mining areas in China are currently suffering severe damage under the disturbance of large-scale mining activities (Bian et al., 2010; Bian et al., 2012; Huang et al., 2015). Thus, the implementation of ecological protection and vegetation restoration measures in the opencast mining areas is urgent and necessary. According to recent statistics (Huang et al., 2015), 75% of the added value of coal production worldwide originates from opencast coal mining, and in China, opencast coal production occupies 15% of the total coal production. In recent years, the development of coal resources in China has gradually moved toward the semi-arid areas. The exploitation of coal mines has caused a series of environmental problems, such as ground subsidence (Loupasakis et al., 2014; Dong et al., 2015), vegetation degradation (Pandey et al., 2014; Qian et al., 2014), soil erosion (Neshat et al., 2014) and heavy metal pollution (Liu et al., 2016).

Vegetation status can reliably reflect the ecological degeneration and restoration in the opencast mining areas in the semi-arid areas. As such, knowledge about the dynamics of vegetation is essential in understanding the disturbance and recovery of local ecosystems (Sun et al., 2010; Liu et al., 2016). During the last decades, numerous sensors have been developed, holding the geometric and spectral characteristics associated with different bands to monitor vegetation dynamics. Examples include the Moderate Resolution Imaging Spectroradiometer (MODIS), the National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer (NOAA/AVHRR), and the Systeme Probatoire d'Observation de la Tarre/VEGETATION (SPOT/VGT) (Gurgel and Ferreira, 2003; Kross et al., 2011; Perez et al., 2016). Moreover, several indices are used to represent the vegetation growth conditions, among which the Normalized Difference Vegetation Index (NDVI) is the most widely used to survey vegetation cover. The higher NDVI values are associated with the higher vegetation cover. Currently, the NDVI time series of satellite sensors with the high time resolution has been widely adopted in detection of vegetation changes (Nordberg and Evertson, 2005; Sun et al., 2010; Sun et al., 2016; Pei et al., 2018), classification of vegetation cover (Yan et al., 2015; Zoungrana et al., 2018), and extraction of vegetation phenological parameters (Kross et al., 2011; Paulina et al., 2017).

During the exploitation process of opencast coal mines in the semi-arid areas, activities including coal mining, coal gangue discharge and vegetation restoration inevitably exert impacts on the vegetation growth characteristics at the spatial and temporal scales. However, few studies have focused on these impacts and the spatio-temporal dynamics of vegetation during the exploitation process of opencast coal mines are still unclear. In fact, traditional research mostly focused on the classification of vegetation cover and the characteristics of the spatio-temporal dynamics of vegetation (Latifovic et al., 2005; Kusimi, 2008; Zhang et al., 2016). Nevertheless, it is difficult to further improve the accuracy of the quantitative expression when the time dimension that describes the critical process is over generalized (Sen et al., 2012; Li et al., 2015). Moreover, this process can be time-consuming. The NDVI series for a long-term period can continuously record the dynamics of vegetation under complex mining activities; thus, it has been popular in recent years. Unfortunately, most studies on NDVI with long-term data series focused only on the general understanding of changes in the overall vegetation, without considering the differences of areas with different functions, such as coal mining areas and restoration areas (Wu et al., 2009; Liu et al., 2016; Prosperbasommi et al., 2016).

The spatial and temporal change characteristics of vegetation are inseparable. The spatial and temporal patterns of vegetation disturbance can be revealed through the decomposition of space-time components (Lei et al., 2016). By investigating different functional regions of the Daliuta coal mining area in Shanxi Province, China, Wang et al. (2017) made significant progress on the research of the amplitude and duration of vegetation disturbance and restoration. However, the impacts of mining activities on the ecological environments around the mining area were not considered in their study. Generally speaking, most of the previous studies mainly focused on the dynamics of vegetation only in the mining areas (Karan et al., 2016; Yang et al., 2018) and the results were insufficient in describing the complex impacts of coal mining activities.

It has been proved that the MODIS-NDVI datasets have sufficient spatial resolution, spectral resolution and temporal resolution to quantitatively capture the dynamic changes of vegetation in space and time. In this study, based on the MODIS NDVI 13Q1 datasets, we applied the linear regression method (LRM), the coefficient of variation (CoV), the spatial buffer analysis (SPA) and the change amplitude and the rate of change in the average NDVI to synthetically explore the spatio-temporal dynamics of vegetation in Jungar Banner at the large (Jungar Banner and three mine groups) and small (three types of functional areas) scales during 2000–2017. The purposes of this study were to explore: (1) the temporal variations of vegetation; (2) the change trends and fluctuation degrees of vegetation in space; and (3) the disturbance distances of coal mining activities on vegetation in Jungar Banner.

2 Materials and methods

2.1 Study area

The study area, covering an area of 7.55×10^3 km^2, is located in Jungar Banner (39°16′–40°20′N, 110°05′–111°27′E; 1100–1250 m a.s.l.) in the eastern part of Inner Mongolia Autonomous Region, China. The topography is high in the northwest and low in the southeast. The main topographic features include arsenic sandstone, aeolian sand and loess gully. This area has barren soil and is ecologically vulnerable. It is characterized by a semi-arid climate with uneven precipitation distribution, mainly concentrating in summer. The average annual precipitation is 408 mm, while the average annual evaporation is about 2100 mm. The annual average temperature is 7.2°C. The Yellow River is the largest surface water body in Jungar Banner. It is not only a regional discharge channel of surface water and groundwater, but also the supply source of groundwater in this area. Jungar Banner is a national comprehensive energy base characterized by both high intensity and large scale in coal exploitation. Mineral resources are mainly distributed in the western, southwestern and eastern parts of Jungar Banner (Fig. 1a). The mine group in the western part is mainly characterized by earth-rock mountainous hills, while the mine groups in the southwestern and eastern parts are mainly characterized by loess hills (Figs. 1b–d).

2.2 Data collection and processing

The MODIS-NDVI 13Q1 data were derived from the National Aeronautics and Space Administration (NASA) Earth Observation System (EOS) (http://reverb.echo.nasa.gov/reverb/). A total of 409 MODIS-NDVI images with a spatial resolution of 250 m and a temporal resolution of 16 d (h26v05 and h26v04) covering the period from March 2000 to December 2017 were collected. The original HDF format was transformed into the GeoTiff format, while the original sinusoidal projection was transformed into the WGS84/UTM projection using the MODIS Reprojection Tool. We processed the NDVI time series data through the maximum synthesis method to avoid the impacts of clouds, atmosphere and solar elevation angle. Then, we calculated the annual average data to remove the impact of the extreme yearly abnormal climate on the growth status of vegetation, utilizing the mean value method (Jiang et al., 2015). Finally, we clipped out the NDVI time series data with the vector boundary of Jungar Banner. Digital Elevation Model (DEM) data were derived from the Geographical Information Monitoring Cloud Platform (http://www.dsac.cn/). These data were projected as WGS84/UTM with a spatial resolution of 30 m. The preprocessing of data included the following steps: resampling, image mosaic and clipping with the vector boundary of Jungar Banner.

In each mine group, we selected three types of functional areas (opencast coal mining excavation areas (MA), reclamation areas (RA) and natural areas (NA)) to study the dynamics of vegetation at the small scales. The locations of the coal mining areas and the typical functional areas (MA, RA and NA) were provided by the Environmental Restoration and Management Center of Jungar Banner mining area. After the field investigation, we identified MA, RA and NA in the three mine groups with the help of local government, and the results are shown in Figures 1b–d. The main plant species in the RA were *Medicago sativa* L., *Astragalus propinquus*
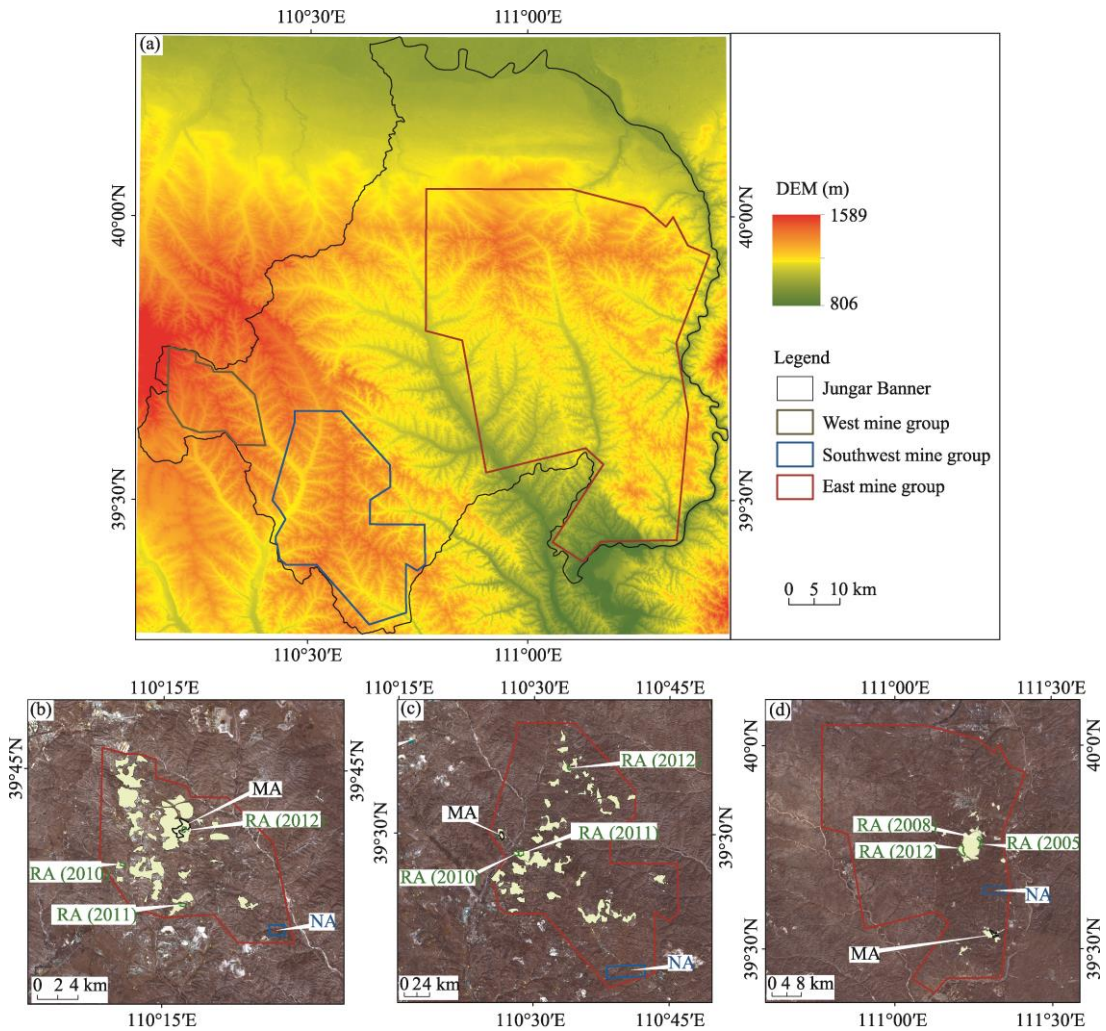
Fig. 1 Digital elevation model (DEM) of Jungar Banner and locations of the three mine groups in Jungar Banner (a) and overview of the coal mining areas (yellow background) inside the three mine groups (red borders; b, west mine group; c, southwest mine group; d, east mine group), as well as locations of the three types of functional areas. The three types of functional areas include: opencast coal mining excavation areas (MA), marked in black letters (for the mine name) and black lines (for the borders); reclamation areas (RA), marked in green letters (for different years) and green lines (for the borders); and natural areas (NA), marked in blue letters and blue lines (for the borders).

Schischkin, *Melilotus officinalis* (L.) Pall, *Artemisia* and *Hippophae rhamnoides* Linn; and the main plant species in the NA were *Stipa bungeana* Trin., *Lespedeza davurica* (Laxm.) Schindl., *Potentilla bifurca* L., *Cleistogenes songorica* (Roshev.) Ohwi and *Artemisia frigida* Willd.

2.3 Methodology

2.3.1 Temporal change analysis of vegetation cover

In this study, we used the change amplitude and the rate of change in the average NDVI (Eqs. 1 and 2, respectively) to comprehensively explore the temporal characteristics of vegetation in a specific time period both at the large (i.e., Jungar Banner and three mine groups) and small (i.e., three typical functional areas) scales.

$$M = \text{NDVI}_b - \text{NDVI}_a, \tag{1}$$

$$N = \frac{\text{NDVI}_b - \text{NDVI}_a}{\text{NDVI}_a} \times \frac{1}{T} \times 100\%, \tag{2}$$

where M is the change amplitude of the average NDVI during the study period; $NDVI_a$ and $NDVI_b$ are the average NDVI values in different functional areas at the beginning and end of the study period, respectively; N is the rate of change in the average NDVI during the study period (%); and T is the time period.

2.3.2 Spatial change analysis of vegetation cover

The LRM is based on the principle of the least square method, in which time is the independent variable and NDVI of each pixel is the dependent variable. Using remote sensing data from 2000 to 2017, we obtained the slope of the fitting regression line (Eq. 3) by linear regression at each grid point (Tian et al., 2015; Wang, 2016; Hu et al., 2019). A positive β_{slope} value means an increasing trend of NDVI, while a negative value indicates a decreasing trend of NDVI. Besides, a T-test was used to test the significance of the change trend for the pixels. T-test was used to verify the real relevance of the two variables and the significant level of the variation trend. According to the results of the test, the trends of NDVI values were divided into the following six levels: highly significant decrease ($P<0.01$), significant decrease ($0.01<P<0.05$), non-significant decrease ($P>0.05$), non-significant increase ($P>0.05$), significant increase ($0.01<P<0.05$) and highly significant increase ($P<0.01$) (Xia et al., 2015).

$$\beta_{slope} = \frac{n \times \sum_{i=1}^{n} i \times NDVI_i - \sum_{i=1}^{n} i \times \sum_{i=1}^{n} NDVI_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2}, \tag{3}$$

where β_{slope} is the slope of the trend line; n is the year, which equals to 18; i is the value of the independent variable ($i=1, 2, \ldots, 18$ for years 2000, 2001, …, 2017, respectively); and $NDVI_i$ is the value of the dependent variable in the ith year.

The vegetation condition shows a great variation among different grid points. The CoV can represent the fluctuation characteristics of NDVI over a period of time (Milich and Weiss, 2000; Weiss et al., 2001; Vicente-Serrano et al., 2006). It can be used as an important indicator of productivity and growth of vegetation after a positive or negative disturbance. The CoV was calculated by Equation 4.

$$CoV = \frac{\sigma}{\mu} = \frac{\sqrt{\frac{1}{n} \times \sum_{i=1}^{n} \left(NDVI_i - \overline{NDVI_i}\right)^2}}{\frac{1}{n} \times \sum_{i=1}^{n} NDVI_i}, \tag{4}$$

where CoV is the coefficient of variation calculated from the mean (μ) and standard deviation (σ) of the NDVI time series in each pixel; and $\overline{NDVI_i}$ is the average of NDVI for the study period.

A higher CoV value for a given pixel indicates a greater fluctuation degree of vegetation, which means that vegetation is vulnerable to external interference, and vice versa. Following the descriptions of Sun et al. (2010), we divided the fluctuation degrees of vegetation into five levels: low fluctuation (CoV values of 0.00–0.15), medium-low fluctuation (0.15–0.25), medium fluctuation (0.25–0.45), medium-high fluctuation (0.45–0.65) and high fluctuation (>0.65).

2.3.3 Analysis of disturbance distances of coal mining activities on vegetation

Using the coal mining boundary of the three mine groups as the buffer origin, we performed a spatial buffer analysis based on the spatial analysis tools of the ArcGIS 10.2 software, with buffer distances of 300, 500, 800, 1000, 1500, 2000, 2500, 3000, 4000, 5000, 6000, 7000, 8000, 9000 and 10,000 m. We used mask technology to exclude the influence of the construction land on the results. The change of the average NDVI value and the CoV were calculated to identify the disturbance distances of coal mining activities on vegetation.

2.3.4 Statistical analyses

In this study, all the statistical analyses were performed using Microsoft Excel 2013 and all the figures and the fitted curves were plotted using Origin 9.0 software (OriginLab Corporation, Northampton, Massachusetts, USA). Furthermore, for each pixel, the slope and CoV were calculated by programming in MATLAB R2014a (MathWorks Corporation, Natick, Massachusetts, USA).

3 Results

3.1 Temporal changes of vegetation cover

3.1.1 Temporal variations of the average NDVI at the large scales

During 2000–2017, the average NDVI of Jungar Banner and three mine groups (west, southwest and east) showed a clear rising trend (Fig. 2). The vegetation growth patterns were also basically similar. However, the change amplitude and the rate of change in the average NDVI varied differently. During 2000–2009, the average NDVI in the three mine groups (west, southwest and east) increased by 0.17, 0.20 and 0.13, respectively, while the rates of change in the average NDVI were 9.36%, 8.66% and 5.04%, respectively. It was found that the west mine group had the maximum rate of change in the average NDVI and a medium change amplitude of the average NDVI. During 2009–2017, both the change amplitudes (0.01, 0.03 and 0.06, respectively) and the rates of change (0.25%, 0.77% and 1.51% respectively) in the average NDVI in the west, southwest and east mine groups were significantly lower than those during 2000–2009. Besides, during 2009–2011, most coal mines were constructed, with inevitable vegetation degradation. Consequently, the average NDVI in the three mine groups (west, southwest and east) decreased (reducing amplitudes of 0.11, 0.10 and 0.08, respectively), and the rates of change in the average NDVI were –9.51%, –7.32% and –6.10%, respectively. The highest values of the reducing amplitude and the rate of change in the average NDVI were observed in the west mine group.
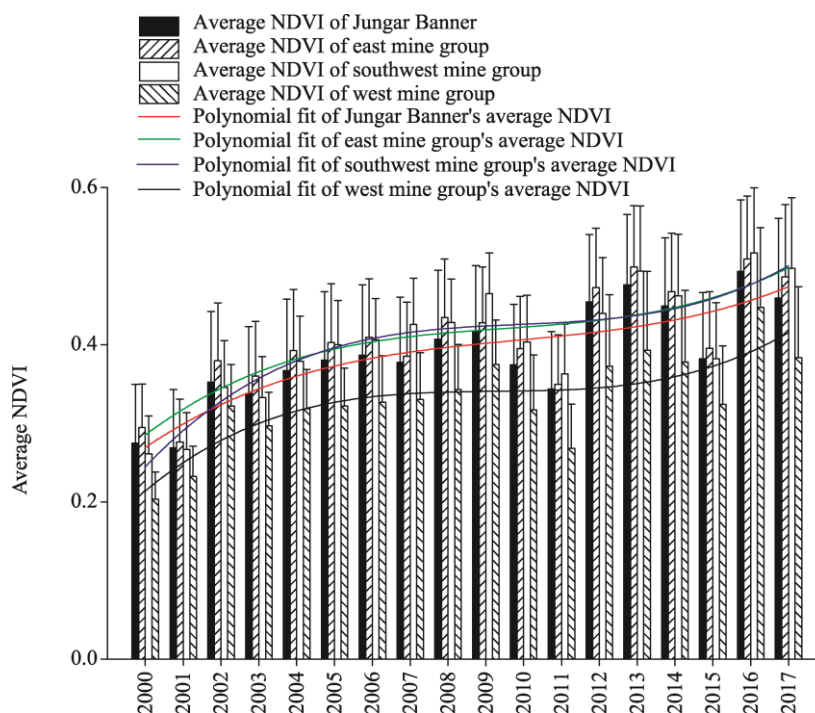

Fig. 2 Average NDVI of Jungar Banner and three mine groups (west, southwest and east) and the corresponding change trends during 2000–2017. The fitted curves were simulated by the Cubic Curve-fitting lines. Bars mean standard errors.

3.1.2 Temporal variations of the average NDVI at the small scales

The average NDVI of the NA in the three mine groups had a significant upward trend (Fig. 3). The maximum average NDVI of the NA in the west mine group was 0.57 in 2016, with an increasing amplitude of 0.29 and a rate of change of 6.63% for the average NDVI. The maximum average NDVI of the NA in the southwest mine group was 0.58 in 2017, with an increasing amplitude of 0.26 and a rate of change of 4.46% for the average NDVI. The maximum average NDVI of the NA in the east mine group was 0.59 in 2016, with an increasing amplitude of 0.30 and a rate of change of 6.16% for the average NDVI. No significant differences were found in the temporal changes of the average NDVI in the NA for the three mine groups. This indicates that vegetation growth condition in the NA was relatively stable.
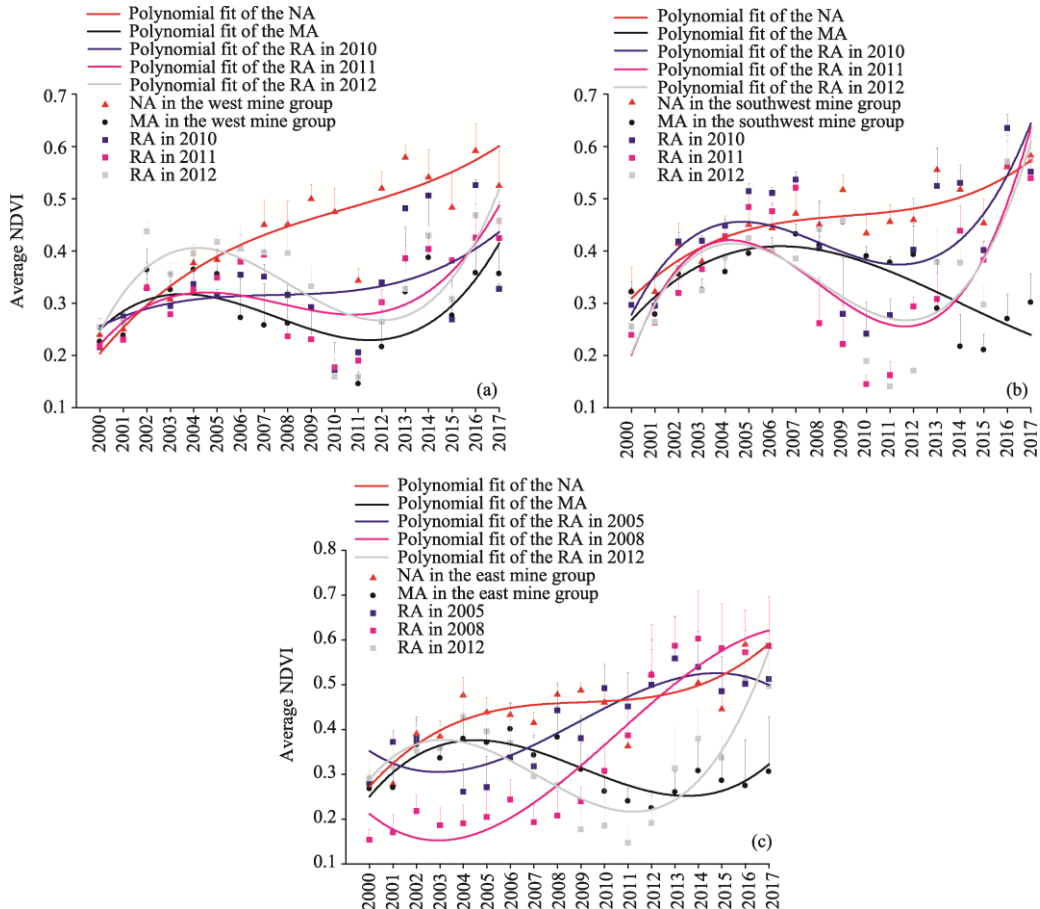

Fig. 3 Average NDVI of different functional areas (MA, RA and NA) in the three mine groups (west, southwest and east) and their change trends during 2000–2017. (a), west mine group; (b), southwest mine group; (c), east mine group. The fitted curves were simulated by the Cubic Curve-fitting lines. Bars mean standard errors.

There was a clear change in the average NDVI of the MA before and after the construction of mining areas (Fig. 3). The mining activities in the MA of the west mine group began in 2006. The decreasing amplitude of the average NDVI was 0.08, with a rate of change of –23.46% before and after the mining activities. At the same time, the average NDVI fell to a minimum of 0.15 in 2011. The mining activities in the MA of the southwest mine group began in 2013. The decreasing amplitude of the average NDVI was 0.10, with a rate of change of –26.15% before and after the mining activities. Besides, the average NDVI fell to a minimum of 0.21 in 2015. The mining activities in the MA of the east mine group began in 2010. The decreasing amplitude of the average NDVI was 0.07, with a rate of change of –18.63% before and after the mining activities. At the same time, the average NDVI fell to a minimum of 0.22 in 2012. Generally speaking, the

temporal changes of the average NDVI in the opencast mine areas experienced a sudden decline at the beginning of coal mining activities, which is due to the loss of surface vegetation and the stacking of solid waste.

The average NDVI values increased quickly with the vegetation reclamation in the mining areas (Fig. 3). In the west mine group, the average NDVI in the RA where the vegetation reclamation was conducted in 2010 showed a clear rising trend until 2014 (Fig. 3a). The change amplitude and the rate of change in the average NDVI were 0.33 and 48.26%, respectively. The average NDVI in the RA where the vegetation reclamation was conducted in 2011 also showed a clear increasing trend until 2016. The change amplitude and the rate of change in the average NDVI were 0.24 and 24.83%, respectively. In the southwest mine group, the average NDVI in the RA where the vegetation reclamation was conducted in 2010 displayed a significant increasing trend from 2010 to 2014 (Fig. 3b). The change amplitude and the rate of change in the average NDVI were 0.29 and 29.87%, respectively. In the RA where the vegetation reclamation was conducted in 2011, the average NDVI showed a clear rising trend until 2016. The change amplitude and the rate of change in the average NDVI were 0.40 and 49.37%, respectively. In the east mine group, the reclamation time occurred earlier than the other two mine groups. The average NDVI showed a significant increasing trend from 2005 to 2010 in the RA where the vegetation reclamation was conducted in 2005; then, the average NDVI changed slightly and tended to be stable at about 0.52 after 2014 (Fig. 3c). The change amplitude and the rate of change in the average NDVI were 0.28 and 16.38%, respectively. In the RA where the vegetation reclamation was conducted in 2008, the average NDVI showed a clear rising trend during 2008–2014; and, the average NDVI fluctuated slightly and tended to be stable at about 0.58 after 2015. The change amplitude and the rate of change in the average NDVI were 0.40 and 31.71%, respectively. Further, in the RA where the vegetation reclamation was conducted in 2012, the average NDVI showed an increasing trend during 2012–2016, with a change amplitude of 0.32 and a rate of change of 42.41% for the average NDVI.

Generally, the vegetation in the RA could recover from the mining disturbance within 3–5 a, to reach a well condition that might be considerably better than the condition before the mining activities. However, after the fifth year, the vegetation began to decline slightly. As time went on, the average NDVI gradually stabilized. These results indicate that the reclaimed vegetation experienced a trend of increase (corresponding to 3–5 a after reclamation)-decrease (corresponding to the sixth year of reclamation)-stability in the coal mining areas.

3.2 Spatial changes of vegetation cover

3.2.1 Characteristics of vegetation cover change

In this study, we divided the vegetation cover conditions in Jungar Banner into five levels: bare land (NDVI values of 0.00–0.15), low vegetation cover (0.15–0.30), medium-low vegetation cover (0.30–0.45), medium vegetation cover (0.45–0.60) and high vegetation cover (0.60–0.80), following the result of Zhang et al. (2016). During 2000–2017, the spatial distribution of inter-annual average NDVI in Jungar Banner showed a "low-high" pattern from west to east and a "high-low-high" pattern from south to north. The regions with medium-low vegetation cover (NDVI values of 0.30–0.45) occupied a large proportion of the total area in Jungar Banner (Fig. 4a). As the elevation increased, the regions with medium vegetation cover (NDVI values of 0.45–0.60) and high vegetation cover (NDVI values of 0.60–0.80) gradually decreased, while the regions with low vegetation cover (NDVI values of 0.15–0.30) increased (Table 1). The regions with medium-low vegetation cover (NDVI values of 0.30–0.45) were almost evenly distributed at different elevation levels.

Through the comparison of vegetation cover among the three mine groups (Fig. 4b), we found that vegetation condition of the west mine group was the worst. Specifically, the regions with NDVI values lower than 0.30 (bare land and low vegetation cover) accounted for 23.01% of the total area in the west mine group, and this area percentage was 21.1% and 19.49% higher than the corresponding area percentages in the southwest and east mine groups, respectively. Besides, the

regions with medium and high vegetation cover (NDVI>0.45) occupied 23.28% of the total area in the east mine group, which was 8.78% and 22.62% higher than those in the southwest and west mine groups, respectively.
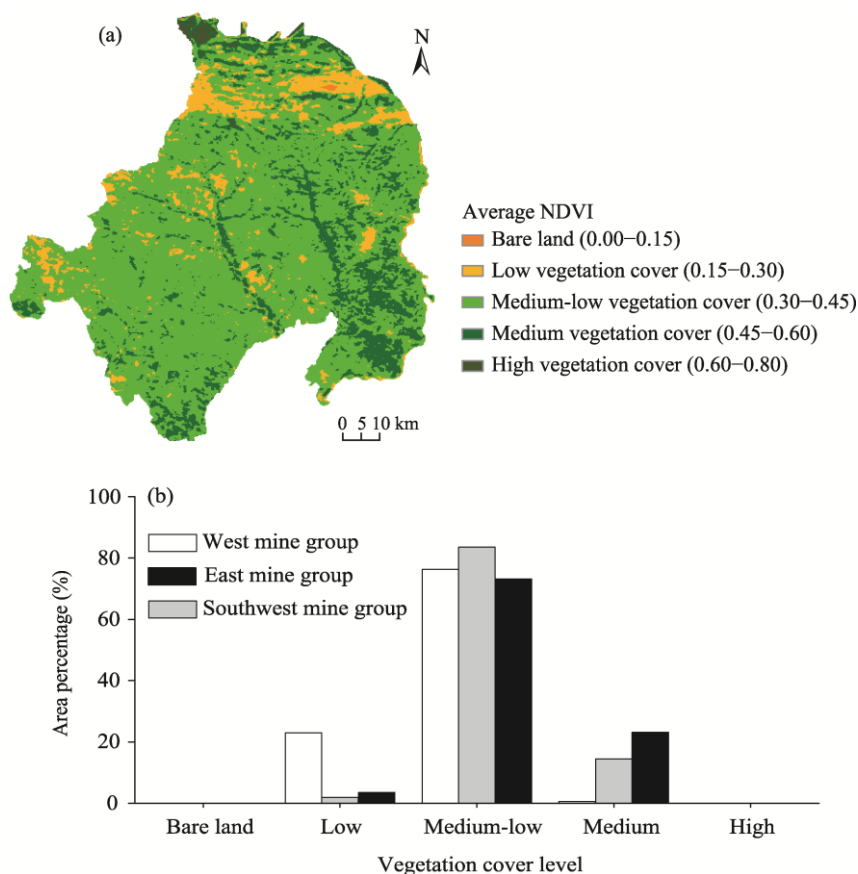
Fig. 4 Spatial distribution of the average NDVI during 2000–2017 in Jungar Banner (a) and area percentages of the regions with different vegetation cover levels in the three mine groups (b)

Table 1 Area percentages of the regions with different vegetation cover levels at various elevations

Vegetation cover level	Area percentage (%)			
	800–1000 m	1000–1200 m	1200–1400 m	1400–1600 m
Bare land (0.00–0.15)	0.46	0.12	0.00	0.00
Low (0.15–0.30)	11.12	11.59	5.33	18.27
Low-medium (0.30–0.45)	56.14	69.97	82.14	80.89
Medium (0.45–0.60)	22.83	17.77	12.49	0.84
High (0.60–0.80)	9.45	0.55	0.04	0.00
Total	100.00	100.00	100.00	100.00

3.2.2 Spatial change trends of vegetation cover

Figure 5 shows the spatial trends of vegetation improvement and degradation in the three mine groups at three time scales (2000–2009, 2009–2017 and 2000–2017). Results show that the regions with vegetation improvement (increase in NDVI values) occupied the majority of the study area. During 2000–2009, the regions where the NDVI showed a highly significant increase ($P<0.01$) accounted for 62.60%, 94.00% and 54.26% of the total area in the west, southwest and east mine groups, respectively. In parallel, area percentages of the regions with the significant increase in NDVI values ($0.01<P<0.05$) were 17.63%, 3.45% and 24.29% in the west, southwest and east mine groups, respectively. The west and southwest mine groups had only small-scale and
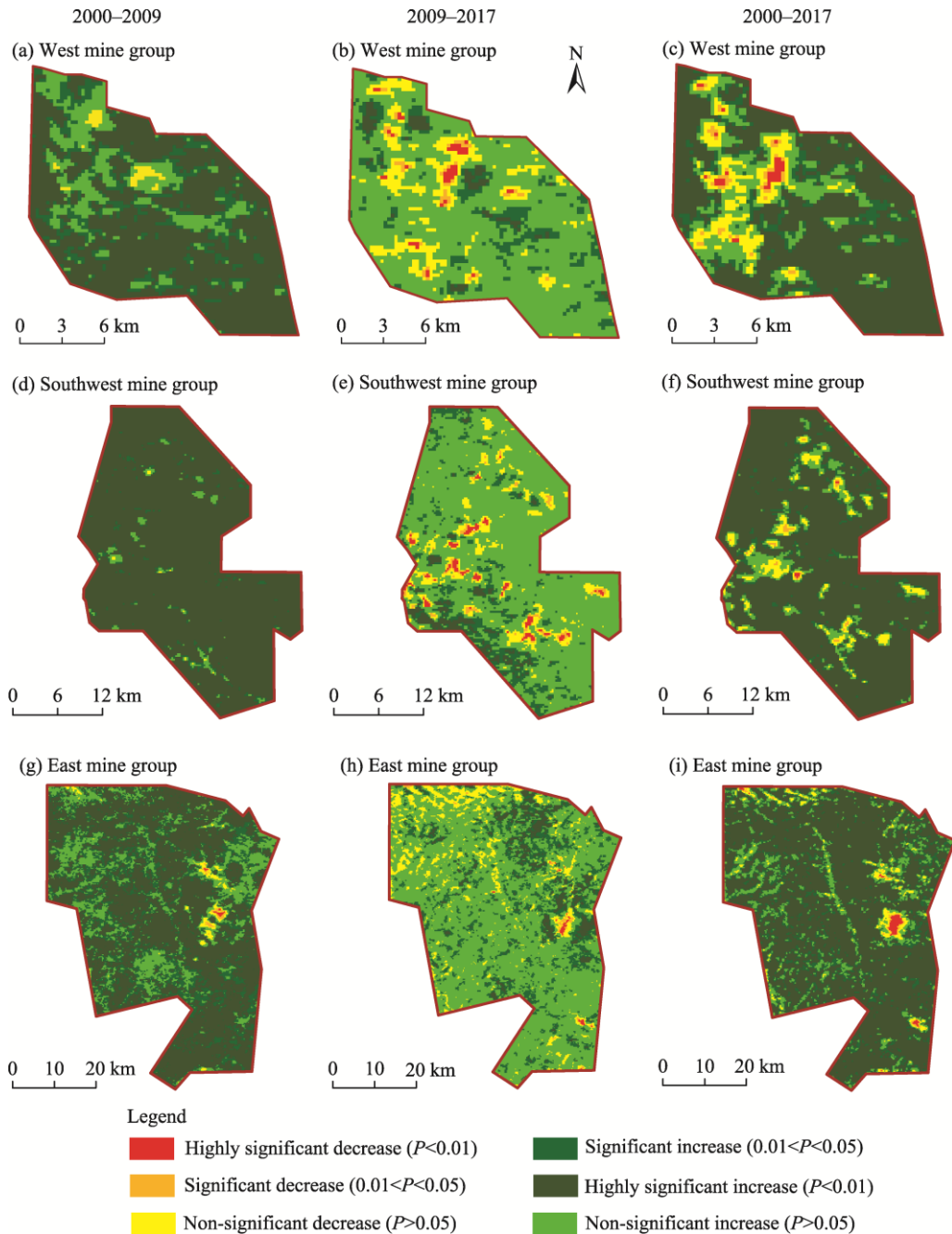
Fig. 5 Spatial distributions of NDVI change trends in the three mine groups (west (a–c), southwest (d–f) and east (g–i)) at three time scales (2000–2009 (a, d, g), 2009–2017 (b, e, h) and 2000–2017 (c, f, i))

dispersed coal mining activities before 2009. The regions with the non-significant decrease in NDVI values in these two mine groups accounted for 1.54% and 0.15% of the total area, respectively (Figs. 5a and d). The regions with the highly significant (area percentage of 0.07%; $P<0.01$) and significant (area percentage of 0.21%; $0.01<P<0.05$) decreases in NDVI values mainly distributed in the east-central mines of the east mine group (Fig. 5g), where the mining activities were initiated in the 1990s. During 2000–2017, the NDVI values in most areas of the three mine groups displayed a non-significant variation. The regions where the NDVI showed a highly significant decrease ($P<0.01$) and a significant decrease ($0.01<P<0.05$) mainly distributed around the coal mining excavation areas (Figs. 5b, e and h). This is due to the large and

continuous mining activities started in these locations around 2009. By comparing the trends of vegetation change during the periods 2000–2009 and 2009–2017, it can be seen that mining activities do have a certain negative impact on vegetation. Further, it was still found that during 2000–2017, the regions with vegetation improvement (increase in NDVI values) still occupied a large area in the three mine groups (Figs. 5c, f and i).

3.2.3   Spatial fluctuation characteristics of vegetation cover

Figure 6 presents the inter-annual CoV values of NDVI in Jungar Banner and in the three mine groups. The inter-annual CoV values of NDVI were mainly between 0.25 and 0.45 (i.e., medium-low fluctuation and medium fluctuation, respectively). The regions with low CoV values of NDVI occupied 10.87%, 4.67% and 14.17% of the total area in the west, southwest and east mine groups, respectively. Accordingly, the regions with medium-low fluctuation of vegetation occupied 73.87%, 84.53% and 79.77% of the total area in the three mine groups, respectively, and the area percentages of the regions with medium fluctuation of vegetation were 15.26%, 10.80% and 5.90%, respectively. In the west and southwest mine groups, there were no regions with medium-high and high fluctuations of vegetation. The regions with medium-high and high fluctuations of vegetation only occupied 0.15% of the total area in the east mine group. From these results it can be seen that, the regions with large fluctuations of vegetation are mainly distributed around the mining areas. The average CoV values of NDVI in the mining areas of the west, southwest and east mine groups were 0.19 (±0.05), 0.22 (±0.06) and 0.27 (±0.09), respectively.

The spatial distributions of inter-annual CoV values of NDVI shown in Figure 6a exhibited clear differences with the spatial distributions of related average NDVI values shown in Figure 4a. The area percentages of the regions with different vegetation fluctuation levels (represented by the inter-annual CoV values of NDVI) versus different vegetation cover levels (represented by the average NDVI values) are presented in Figure 7. The regions with CoV values of NDVI lower than 0.15 mainly occurred in bare land (area percentage 87.9%) and high vegetation cover areas (area percentage of 81.3%). The regions with CoV values of NDVI higher than 0.25 were mostly distributed in low vegetation cover areas (area percentage of 28.8%) and medium-low vegetation cover areas (area percentage of 10.2%), due to mining activities and post-vegetation reclamation.

3.3   Disturbance distances of mining activities on vegetation

Figures 8a1–a3 show that the average NDVI generally increased with the increasing distance from the mining areas. In the west mine group, the average NDVI increased significantly with the increasing distance from 0 to 800 m, while in the range between 800 and 10,000 m, the average NDVI increased slowly at first and then remained stable (at around 0.39) with the increase of distance. In the southwest mine group, the change of the average NDVI was consistent with that in the west mine group in the distance range from 0 to 800 m. However, in the range from 800 to 10,000 m, with the increase of distance, the average NDVI decreased slightly at first and then remained stable at around 0.44. In the east mine group, the average NDVI increased significantly with the increasing distance from the mining areas in the range from 0 to 1000 m. However, in the range from 1000 to 10,000 m, with the increase of distance, the average NDVI decreased slightly at first and then maintained a stable level at around 0.45. These results indicate that the disturbance distances of mining activities on vegetation in the west and southwest mine group were both 800 m, while in the east mine group the distance was 1000 m. This difference may be caused by different mining scales (Yao et al., 2013). The CoV values of NDVI showed a significant downward trend in the range of 0–800 m in the west and southwest mine groups and in the range from 0 to 1000 m in the east mine group (Figs. 8b1–b3). With the increase of distance from the mining areas, the disturbance of coal mining activities on vegetation decreased gradually. The CoV values of NDVI had a slightly upward trend and the vegetation stability increased with the increase of distance from the mining areas in the range of 800–10,000 m in the west and southwest mine groups and in the range from 1000 to 10,000 m in the east mine group.
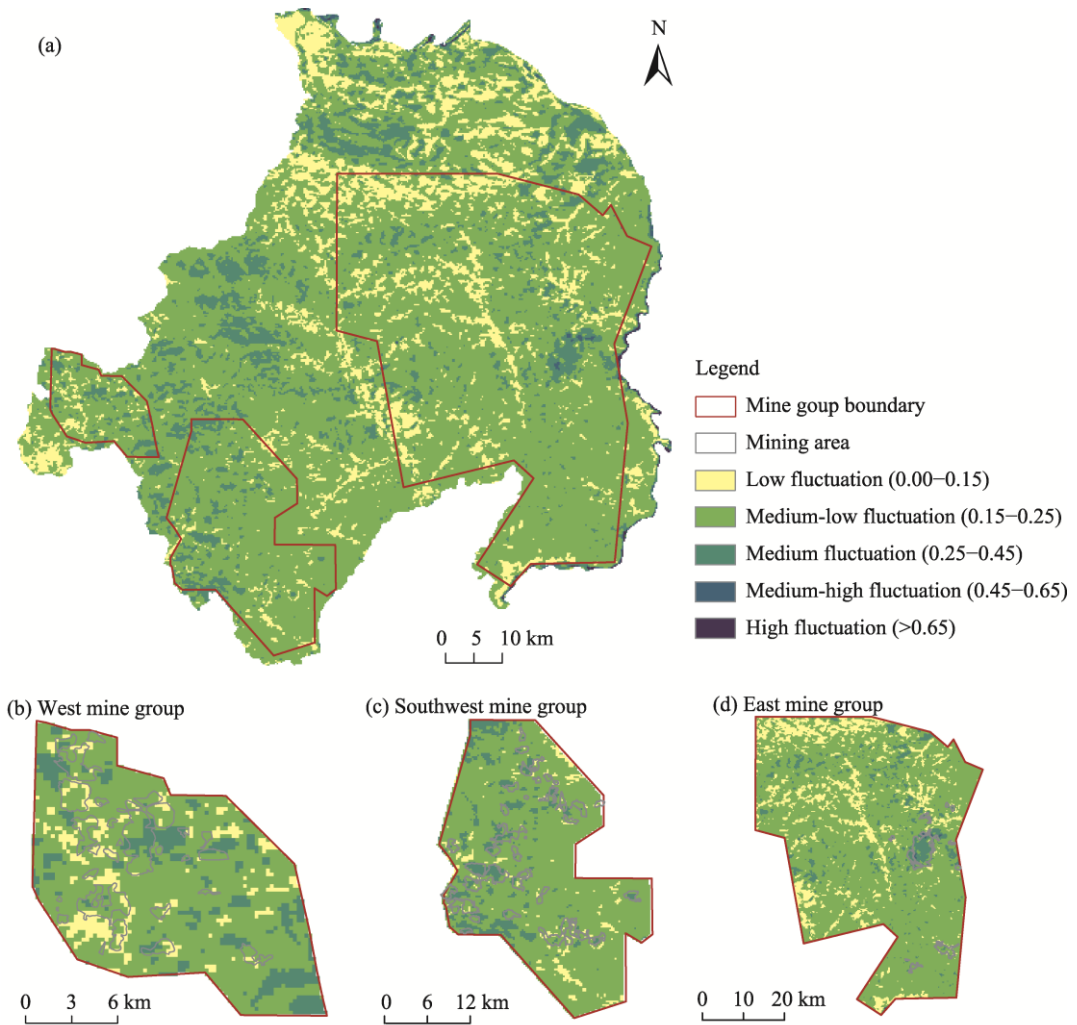
Fig. 6 Spatial distributions of fluctuations of vegetation (represented by the CoV (coefficient of variation) values of NDVI) during 2000–2017 in Jungar Banner (a) and in the three mine groups (b–d)
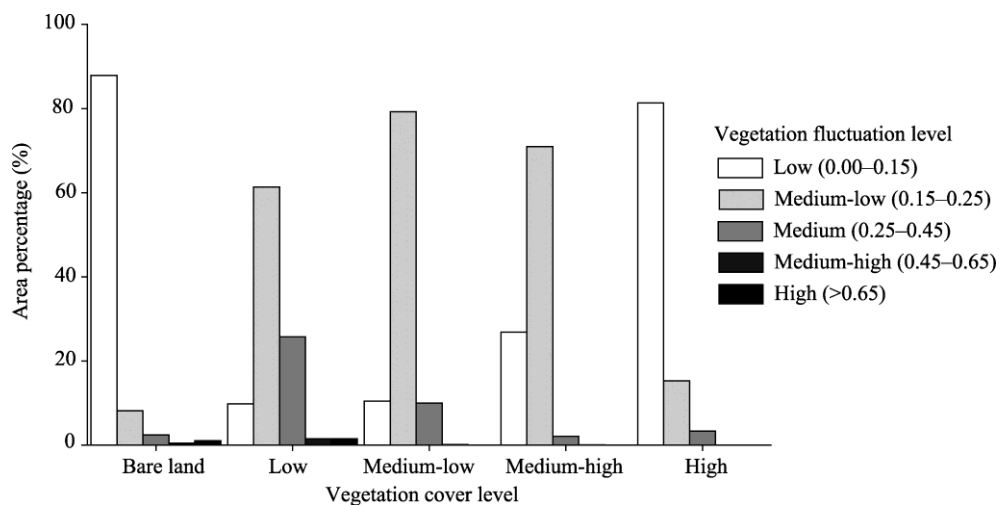

Fig. 7 Area percentages of different vegetation fluctuation levels (represented by the inter-annual CoV values of NDVI) versus different vegetation cover levels (represented by the average NDVI values)
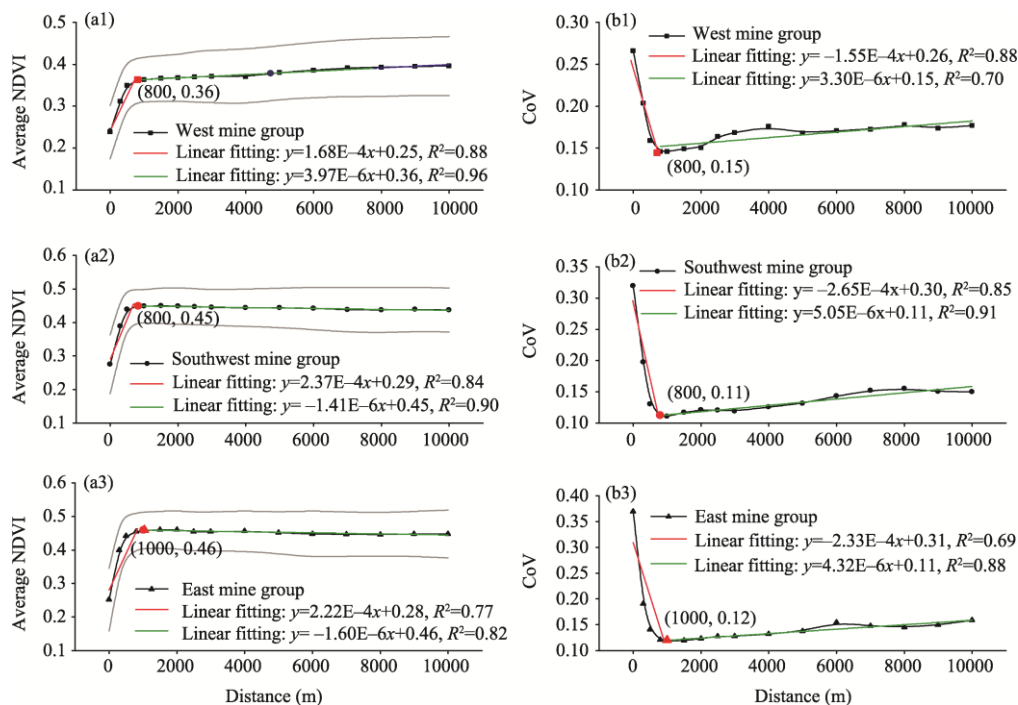
Fig. 8 Relationship between the average NDVI and the distance from the coal mining areas in the three mine groups (a1–a3) and relationship between the CoV values of NDVI and the distance from the coal mining areas in the three mine groups (b1–b3). The grey line represents the standard error line of the average NDVI along with the distance from the coal mining areas; and the red line and green line represent two different change trends of the average NDVI or the CoV value of NDVI along with the distance from the coal mining areas. The two values in the bracket indicate the distance and the average NDVI or the CoV of NDVI, respectively.

4 Discussion

Mining activities usually exert negative impacts on local vegetation (Wang et al., 2017). The spatio-temporal dynamics of vegetation should be assessed before implementing vegetation reclamation plans. However, previous studies on investigating the characteristics of vegetation in the mining areas were over-simplistic (Li et al., 2015; Lei et al., 2016). The findings of this study expand prior works. At the large scales, the temporal changes of the average NDVI in the three mine groups showed an upward trend. At the small scales, the vegetation in the artificial RA (in this study) could recover from the mining disturbance within 3–5 a. This was significantly different from the vegetation in the RA. As indicated by Lovich and Bainbridge (1999), the vegetation usually takes 15–30 a for the natural succession in a shrub-grass community, and 100 a or more for a forest community. Therefore, the recovery of a seriously disturbed ecosystem (which has a weak self-recovery ability) is impossible by relying on its natural resilience (Wang et al., 2013). Our study shows that artificial vegetation restoration can greatly shorten the restoration time. The differentiation of NDVI became increasingly clear with the increase of restoration time. The temporal change regulation of vegetation in the RA of Jungar Banner (this study) differed from that in the opencast coal mining areas of grasslands in Xilinhot of Inner Mongolia (Zhang et al., 2016). This is probably due to the fact that the plants of vegetation restoration in the opencast coal mines of grasslands mainly include herbs, which are better adapted to the exposed soil surface and barren land in the early stage of restoration, and can reproduce rapidly during the rainy season (Brown et al., 1997). However, the herbs usually degenerate after about 3 a. The selection and configuration of vegetation structure should be considered in the RA. Although the initial control effects of shrubs and trees on the dump of coal mines are not as good as those of herbs, they can provide a long-term or permanent environmental

benefit. In the MA, the vegetation deteriorated rapidly as soon as the beginning of opencast mining activities. It is reported that the opencast mining is far more destructive than the underground mining (Zhao et al., 2012; Wang et al., 2017). The rate of change in the average NDVI in the NA of the three mine groups was less than 7%, while that in the RA was significantly higher, in the range of 20%–60%. This may be related to the organic carbon sequestration in the soil (Ussiri et al., 2006; Zhang et al., 2019).

Figure 9 shows the conceptual model of soil organic carbon (SOC) dynamic in the NA, MA and RA of the study area. It should be noted that we modified the model according to the result of Ussiri and Lal (2005). With the increase of reclamation time, the SOC content in the RA will even exceed the level of the NA after several years. This means that the average NDVI of the RA will be higher than that of the NA. We found that the average NDVI of the RA in 2010 in the southwest mine and of the RA in 2008 in the east mine exceeded the average NDVI of the NA in the sixth year after reclamation (Fig. 3).
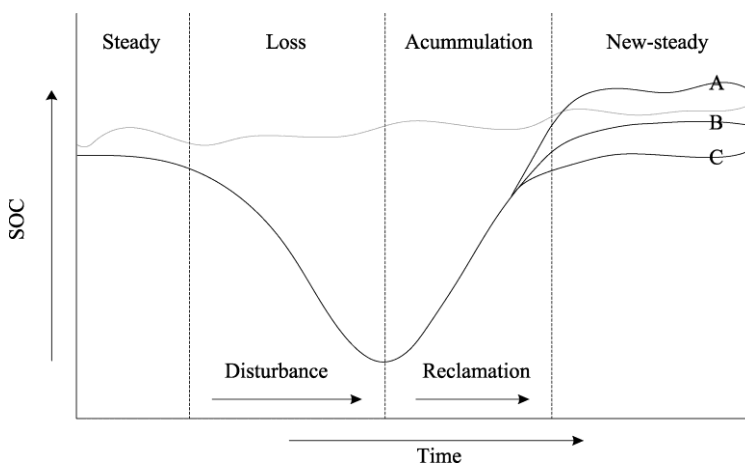

Fig. 9 Conceptual model of soil organic carbon (SOC) dynamic in the NA, MA and RA. The modified model was derived from the result of Ussiri and Lal (2005). The gray line represents the SOC dynamic in the NA, and the black lines represent the SOC dynamic in the MA and RA. The line A shows that the SOC of the RA is higher than that of the NA, the line B shows that the SOC of the RA is similar to that of the NA, and the line C shows that the SOC of the RA is lower than that of the NA.

This study is in agreement with previous studies on the fact that the spatial distribution pattern of vegetation cover in the mining areas is determined by both natural and human factors (Zhang et al., 2016). Liu et al. (2016) discovered a significant positive correlation between NDVI and elevation, because of the plenty of sunlight in the high elevation regions. On the contrary, we found that the regions with medium-high and high vegetation cover gradually reduced with the increase of elevation (Table 1). The adequacy of soil moisture is the key factor in explaining the difference in these research results. In the semi-arid areas, the higher the terrain is, the more intense the evaporation and the easier the loss of soil moisture are (Lei, 2010). Thus, soil moisture is the most important limiting factor of vegetation growth in the mining areas (Bian et al., 2009; Lei et al., 2010). However, the west mine group in the study area is characterized by sandy soil with loose texture and poor cohesion; here, mining activities bared the ground surface and exacerbated soil moisture loss (Lei and Bian, 2014; Liu et al., 2018, 2019), which in turn affected vegetation growth. The lack of topsoil may also result in poor vegetation condition (He et al., 2015; Liu et al., 2016). Therefore, the vegetation condition of the west mine group was the worst among the three mine groups investigated in this study.

Considering the spatial change trends of vegetation, we found that the year 2009 was a temporal breakpoint. Before 2009, the ratio of vegetation improvement area to vegetation degradation area in the three mine groups (west, southwest and east) was 64:1, 664:1 and 62:1, respectively (Table 2). After 2009, the development of high-intensity and large-scale coal mining

activities has led to widespread environmental problems. The area of vegetation improvement was significantly reduced, while the area of vegetation degradation increased. The ratio of vegetation improvement area to vegetation degradation area in the three mine groups (west, southwest and east) was 8:1, 20:1 and 33:1, respectively, during the period from 2000 to 2017 (Table 2). These results indicate that vegetation reclamation improves the overall vegetation condition (Wu and Pauw, 2010). Regional vegetation reclamation could compensate the negative impact of mining activities on vegetation (Lei, 2010; Tian et al., 2014). Besides, the new green coal mining technology can also decrease the disturbance of mining activities on vegetation (Huang et al., 2013). In this study, we found that the regions with the CoV values of NDVI above 0.25 were mainly distributed in both low vegetation cover and medium-low vegetation cover areas. This result shows that the geomorphological pattern of the lower vegetation cover was broken by the new vegetation cover and the CoV values of NDVI increased with the appearance of additional vegetation patches (Lei, 2010). The average CoV value of NDVI in the mining areas with poor vegetation condition (i.e., the west mine group) was relatively low. On the contrary, the average CoV value of NDVI in the southwest and east mine groups was relatively high. We also found that the CoV values of NDVI in the RA were high.

Table 2 Ratio of vegetation improvement area to vegetation degradation area in the west, southwest and east mine groups during the periods of 2000–2009, 2009–2017 and 2000–2017

Period	Ratio of vegetation improvement area to vegetation degradation area		
	West mine group	Southwest mine group	East mine group
2000–2009	64:1	664:1	62:1
2009–2017	5:1	8:1	8:1
2000–2017	8:1	20:1	33:1

The disturbance distances of mining activities on vegetation in the west and southwest mine groups were both equal to 800 m, while it was equal to 1000 m in the east mine group. These values significantly differ from the findings of other studies (Liao and Liu, 2010; Yao et al., 2013). Yao et al. (2013) calculated that the average disturbance distance of opencast coal mining activities on vegetation in the arid desert areas was 3200 m. This difference is possibly due to the fact that the natural background condition of the arid desert areas is worse than that of Jungar Banner in this study. The disturbance distance of mining activities on vegetation varied due to the differences in the intensity and scale of mining activities. Yao et al. (2013) concluded that the disturbance distance of mining activities on vegetation increased with the increase of mining scale. Due to the presence of the large opencast coal mines, the disturbance distance of mining activities on vegetation in the east mine group reached farther than those in the west and southwest mine groups. This indicates that great attentions should be paid to vegetation restoration and environmental management in the regions affected by coal mining diffusion. Our results provide a compelling basis for the environmental protection and vegetation reclamation in the opencast coal mining areas.

5 Conclusions

In this study, we investigated the spatio-temporal dynamics of vegetation in Jungar Banner using various analysis methods. We found that the temporal changes of the average NDVI showed an upward trend at the large scales (Jungar Banner and three mine groups). At the small scales (three typical functional areas), the rates of change of the average NDVI in the RA and MA were considerably higher than that in the NA. Besides, the vegetation in the RA experienced a trend of increase (3–5 a after reclamation)-decrease (the sixth year of reclamation)-stability. Mining activities have exerted negative impacts on vegetation, which could be reduced by vegetation reclamation measures. The regions with CoV values of NDVI lower than 0.15 were mainly located in bare land and high vegetation cover areas, while the regions with CoV values of NDVI higher

than 0.25 were mostly located in low and medium-low vegetation cover areas. The average disturbance distances of mining activities on vegetation in the three mine groups (west, southwest and east) were 800, 800 and 1000 m, respectively. The greater the scale of coal mining, the farther the disturbance distances of mining activities on vegetation. In this study, we only focused on the large scales (i.e., Jungar Banner and three mine groups) and small scales (i.e., three typical functional areas) to describe the spatio-temporal dynamics of vegetation, without considering the differences in vegetation types, which merit further analyses with high spatial resolution remote sensing data. Besides, as climate change has a certain impact on vegetation change, more detailed studies on the relationships between climate factors and vegetation changes are needed in the opencast coal mining areas by acquiring more meteorological data.

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